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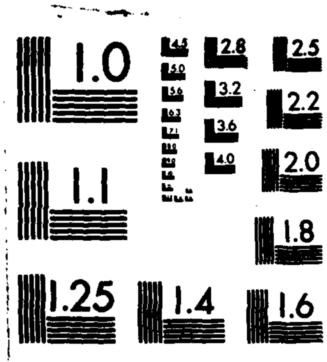

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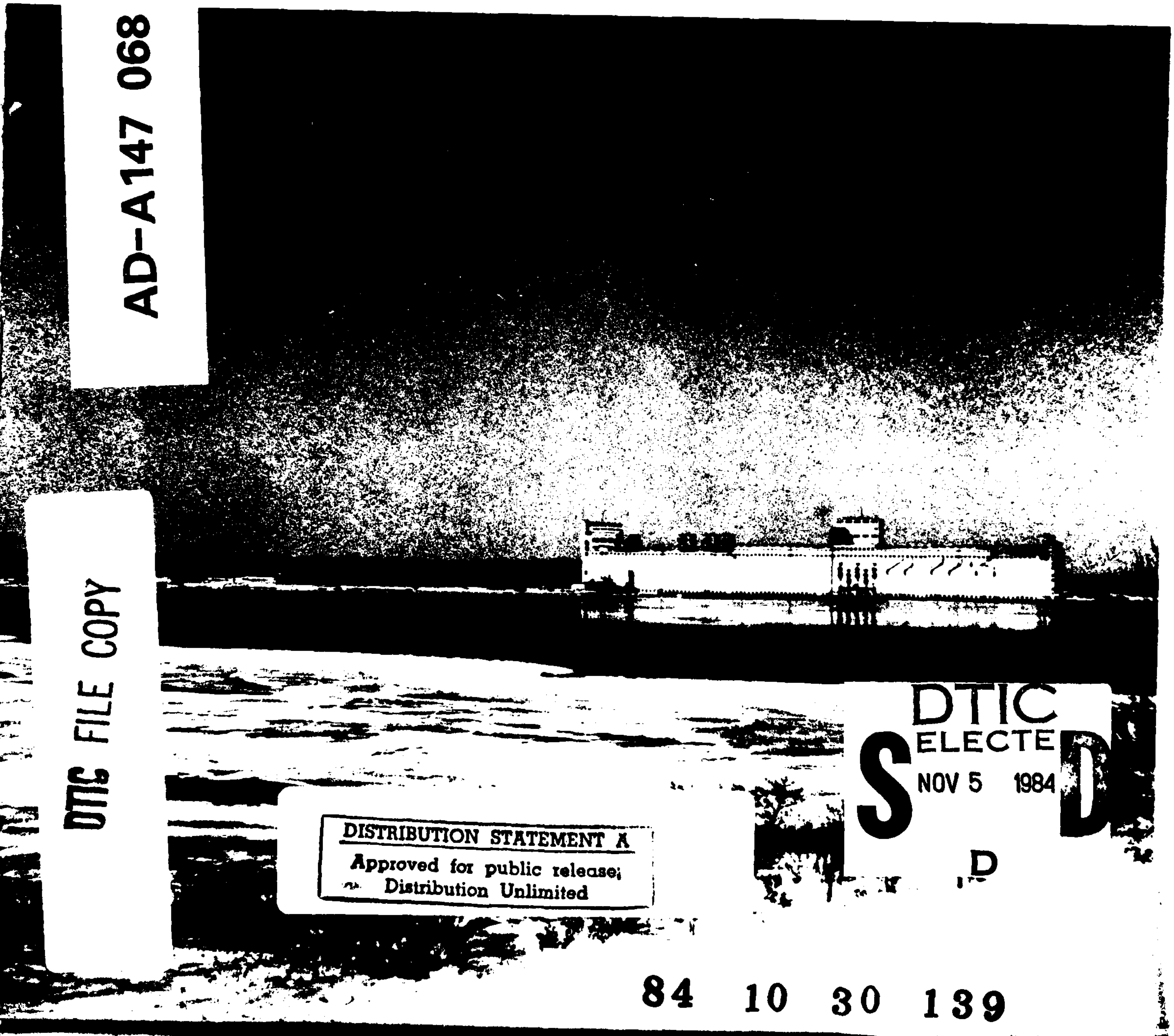
Forecasting water temperature decline and freeze-up in rivers



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

***Cover:** St. Lawrence River ice cover behind Ogdensburg boom.*

CRREL Report 84-19

July 1984

Forecasting water temperature decline and freeze-up in rivers

H.T. Shen, E.P. Foltyn and S.F. Daly

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In this study a method for making long-range forecasts of freeze-up dates in rivers is developed. The method requires the initial water temperature at an upstream station, the long-range air temperature forecast, the predicted mean flow velocity in the river reach, and water temperature response parameters. The water temperature response parameters can be either estimated from the surface heat exchange coefficient and the average flow depth or determined empirically from recorded air and water temperature data. The method is applied to the St. Lawrence River between Kingston, Ontario, and Massena, New York, and is shown to be capable of accurately forecasting freeze-up. Originator-supplied

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PREFACE

This report was prepared by Hung Tao Shen, Professor of Civil and Environmental Engineering, Clarkson University; Edward P. Foltyn, graduate student, Clarkson University; and Steven F. Daly, Research Hydraulic Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was done during Dr. Shen's sabbatical leave at the Ice Engineering Research Branch, CRREL. The support and encouragement of Guenther E. Frankenstein is deeply appreciated.

The authors acknowledge valuable assistance provided by Stephen C. Hung, Ray A. Assel and David Sage. This report was technically reviewed by Dr. George D. Ashton and Donald F. Haynes.

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FORECASTING WATER TEMPERATURE DECLINE AND FREEZE-UP IN RIVERS

H.T. Shen, E.P. Foltyn and S.F. Daly

INTRODUCTION

The formation of an ice cover, or freeze-up, in a river is an important phenomenon that affects winter operations. The ability to provide accurate, long-range forecasts in the fall for the date of initial ice formation in a river is important in scheduling the shipping season, operating hydroelectric plants, planning flow regulation, and scheduling the installation of ice control structures and devices. River ice forms when the water temperature declines from its summer maximum to freezing. The decline of the water temperature is governed by the heat exchange at the air/water interface.

By assuming that the heat exchange is directly proportional to the temperature difference between the water surface and the air, Rodhe (1952) developed an iterative relationship between the mean daily air temperature and ice formation in the Baltic Sea. Using Rodhe's formulation, Bilello (1964) developed a method for predicting river and lake ice formation. Greene (1983) recently developed a procedure for forecasting freeze-up in the St. Marys River by introducing air temperature forecasts into Bilello's method. The Rodhe-Bilello method considers the decay of water temperature as a function of a single site-specific constant. Their formulation does not include the convective effects of the river flow and is therefore not strictly valid for rivers. Poulin et al. (1971) developed a probability forecast method for the water temperature and freeze-up dates in the St. Lawrence River. Instead of incorporating air temperature forecasts in their method, Poulin et al. determined air temperature regimes in terms of probabilities from the past record, and they forecast freeze-up for different probable air temperature regimes. They used the normal decline for the water temperature at the upstream end of the river. Adams (1976) and Assel (1976, 1977) developed freeze-up forecast models for the upper St. Lawrence River based on analytical formulations similar to that of Poulin et al. (1971). Assel incorporated air temperature forecasts in this model, but the normal air temperature was assumed to be constant during each half-month period.

In this report the normal pattern of air temperature variation during a year is examined, and the relationship between variations in air temperature and water temperature is analyzed. On the basis of these analyses, an improved analytical method for predicting water temperature decline and freeze-up is developed. The method is used to develop a computer model for predicting freeze-up in the Eisenhower Lock area of the upper St. Lawrence River near Massena. The results show that long-range forecasts of freeze-up in a river can be made with good accuracy.

Problem formulation

For a well-mixed river the conservation of thermal energy can be represented by a one-dimensional convection-diffusion equation (Brocard and Harleman 1976)

$$\frac{\partial}{\partial t}(\rho\, C_p\, A\, T_w) + \frac{\partial}{\partial x}(Q\, \rho\, C_p\, T_w) = \frac{\partial}{\partial x}(A E_x\, \rho\, C_p\, \frac{\partial T_w}{\partial x}) - B\,\phi \tag{1}$$

where t = time
ρ = density of water
C_p = specific heat of water
A = cross-sectional area of the river
T_w = water temperature
x = distance along the river
Q = river discharge
E_x = longitudinal dispersion coefficient
B = channel width
ϕ = net heat flux from the river per unit surface area.

If we assume that changes in river discharge are not significant, we can simplify eq 1 to the following form:

$$\frac{\partial T_w}{\partial t} + U \frac{\partial T_w}{\partial x} = \frac{\partial}{\partial x}(E_x \frac{\partial T_w}{\partial x}) - \frac{\phi}{\rho\, C_p\, D} \tag{2}$$

where U is the average flow velocity and D is the depth of flow. By neglecting the longitudinal mixing term, we can express eq 2 in its Lagrangian form:

$$\frac{DT_w}{Dt} = -\frac{\phi}{\rho\, C_p D}\ . \tag{3}$$

For a lake with negligible flow velocity, the convective term can be neglected.

The surface heat exchange is a complicated function of ambient atmospheric conditions (Paily et al. 1974). For the present study the following simple relationship is assumed:

$$\phi = h_{wa}\,(T_w - T_a) \tag{4}$$

where h_{wa} is an energy exchange coefficient and T_a is the air temperature. Equations 3 and 4 define a functional relationship between the water temperature and the ambient air temperature.

For long-range freeze-up forecasts, an analytical description of the predicted air temperature is needed for eq 4. Since the long-range air temperature forecast provided by the National Weather Service* is given in terms of deviations from the normal air temperature, an analytical representation of the normal air temperature is needed. The air temperature has cyclic variations of periods of one year as well as variations with shorter periods. This cyclic character of air temperature has been well recognized (Kothandaraman 1971, Song et al. 1973). Time-dependent variations of the air temperature can, therefore, be represented analytically by a Fourier series:

$$T_a = \bar{T} + \sum_{n=1}^{N} \left(C_n \cos \frac{2n\pi t}{T} + S_n \sin \frac{2n\pi t}{T}\right) \tag{5}$$

where T = period of one year

$\bar{T}$ = mean air temperature

C_n, S_n = Fourier coefficients

N = total number of harmonics in the series.

In this study the time variable t starts on 1 October each year. As an example, Fourier series approximations with $N = 10$ for both the air temperature and the water temperature records at Massena, New York, are presented in Figure 1 for the year between 1 October 1977 and 30 September 1978. Coefficients of the Fourier series can be determined from the temperature record using a linear regression procedure such as the GLM procedure in the SAS package (SAS Institute Inc. 1982).

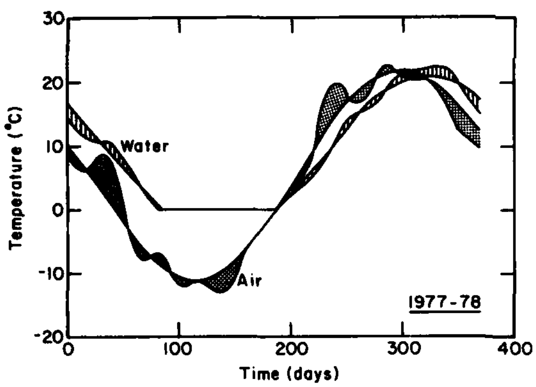


Figure 1. Air temperature and water temperature at Massena, New York, 1 October 1977-30 September 1978.

To determine the appropriate number of terms to be included in the Fourier series representation of the normal air temperature, a simple statistical analysis can be made. The basis of the air temperature record at Massena, New York, for the 33 years between 1948 and 1981, a Fourier series of $N = 12$ is obtained. Table 1 shows the estimated Fourier coefficients and their standard errors. The standard errors of the estimates of the coefficients of harmonics of orders higher than one are of the same order as the estimated values of the coefficients themselves. This indicates that harmonics of periods of less than one year can be considered to be random components and should not be included in the analytical representation of the normal air temperature. To further substantiate this, the air temperature record was fitted by a Fourier series of orders one to twelve.

Monthly and Seasonal Weather Outlook, Climatic Analysis Center, NOAA, Washington, DC.

Table 1. Fourier coefficients for air temperature at Massena, New York, 1948–1981.

Parameter	*Estimate*	*Standard error of estimate*
$\overline{T}$	6.63828048	0.04126520
$C1$	5.86978266	0.05833369
$S1$	-13.09415854	0.05838191
$C2$	0.16598747	0.05833188
$S2$	0.58291816	0.05838374
$C3$	-0.13276961	0.05833649
$S3$	0.05808216	0.05837906
$C4$	-0.29945449	0.05835414
$S4$	0.29958279	0.05836144
$C5$	-0.20162318	0.05832959
$S5$	-0.22805619	0.05838598
$C6$	-0.00503364	0.05833432
$S6$	-0.09626112	0.05838121
$C7$	0.01613923	0.05834101
$S7$	-0.06291826	0.05837450
$C8$	-0.17351080	0.05836790
$S8$	0.09971897	0.05834760
$C9$	0.05038423	0.05834174
$S9$	0.09057839	0.05837374
$C10$	-0.07903248	0.05835328
$S10$	0.22531156	0.05836220
$C11$	-0.00153682	0.05836369
$S11$	0.07895130	0.05835277
$C12$	0.13510373	0.05936695
$S12$	0.01369789	0.05834843

Table 2. Accuracy of Fourier series representations for air temperature at Massena, New York, 1948–1981.

Total number of harmonics, N	*Correlation parameter, R^2*
1	0.8314
2	0.8329
3	0.8330
4	0.8337
5	0.8341
6	0.8341
7	0.8341
8	0.8343
9	0.8343
10	0.8345
11	0.8346
12	0.8346

A value of the correlation parameter R^2 for each Fourier series was calculated (Table 2). The parameter R^2, which measures how much variation in the air temperature can be accounted for by a Fourier series, is the ratio of the sum of the squares of the predicted value divided by the sum of the squares of the recorded values. Table 2 shows that the first harmonic accounts for 83% of the variation in air temperature; the inclusion of additional harmonics in the series does not improve the accuracy of the representation of air temperature significantly. Therefore, the normal air temperature can best be represented by a harmonic function with a period of one year. Higher-order variations cannot be included as parts of the normal air temperature. Since the higher-order variations change from year to year, they can only be accounted for by using forecasts provided by the National Weather Service.

Analytical treatment

Using only the first harmonic in eq 5, the normal air temperature variation can be approximated by

$$T_N = \overline{T} + a \sin\left(\frac{2\pi t}{T} + \theta\right) \tag{6}$$

where T_N = periodic function representing the normal temperature
$a = (C_1^2 + S_1^2)^{1/2}$, the amplitude of the annual temperature cycle
$\theta = \tan^{-1}(C_1/S_1)$, a phase angle.

For a river reach with known water temperature at the upstream end (Fig. 2), an analytical expression for the water temperature at the downstream end can be obtained from eq 3, 4 and 6:

$$\frac{T_{j+1} - \overline{T}_j - a_j \cos\alpha_j \sin\left(\frac{2\pi t}{T} + \theta_j - \alpha_j\right)}{T_{j,o} - \overline{T}_j - a_j \cos\alpha_j \sin\left(\frac{2\pi t_o}{T} + \theta_j - \alpha_j\right)} = e^{-k_j t_{T_j}} \tag{7}$$

where j = subscript representing the location of the river reach
x_j and x_{j+1} = space coordinates of upstream and downstream ends of the reach
t_{T_j} = travel time of a water mass in the reach, $(x_{j+1} - x_j)/U_j$
U_j = mean flow velocity
T_{j+1} = water temperature at (x_{j+1}, t)
$T_{j,o}$ = water temperature at $(x_j, t - t_{T_j})$
$k_j = h_{wa}/(\rho C_p D_j)$, a parameter that measures the sensitivity of water temperature in response to air temperature changes
D_j = mean flow depth
$\alpha_j = \tan^{-1}(2\pi/k_j T)$.

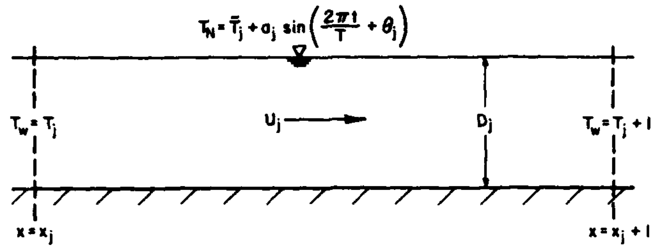


Figure 2. Definition sketch of a river reach.

If the water temperature at a river cross section is known, the water temperature at any number of downstream stations can easily be obtained by successively applying eq 7. For a river system with multiple branches, an equation for conservation of thermal energy is required at a junction:

$$T_D = \sum_{\ell=1}^{L} (T_{u,\ell}\, Q_{u,\ell})/Q_D \tag{8}$$

where T_D = water temperature at the outflow side of the junction
L = total number of incoming branches
$T_{u,\ell}$ and $Q_{u,\ell}$ = water temperature and discharge of an incoming branch, respectively
$Q_D = \sum_{\ell=1}^{L} Q_{u,\ell}$ = outflow from the junction.

When the uppermost station is at the outlet of a lake, the following solution for a well-mixed lake with negligible convective velocity applies:

$$\frac{T_L - \bar{T} - a_L \cos\alpha_L \sin\left(\frac{2\pi t_L}{T} + \theta_L - \alpha_L\right)}{T_o - \bar{T} - a_L \cos\alpha_L \sin\left(\frac{2\pi t_o}{T} + \theta_L - \alpha_L\right)} = e^{-k_L(t_L - t_o)} \tag{9}$$

where T_L = lake water temperature at time t_L
t_o = initial time
T_o = lake water temperature at time t_o
$k_L = h_{wa}/(\rho C_p D_L)$
D_L = mean depth of the lake

$\alpha_L = \tan^{-1}(2\pi/k_L T)$

a_L and θ_L = amplitude and phase angle of the air temperature, respectively.

If $t_o << t_L$, then eq 9 becomes

$$T_L = \overline{T} + a_L \cos\alpha_L \sin\left(\frac{2\pi t_L}{T} + \theta_L - \alpha_L\right). \tag{10}$$

Equation 10 shows that the amplitude of the water temperature in a lake is equal to the amplitude of the air temperature multiplied by $\cos\alpha_L$. The water temperature variation lags behind the air temperature by a phase angle α_L. The mean water temperature is equal to the mean air temperature. When the headwater of a river is not a lake, one can use eq 9 to represent the water temperature variation at the headwater by treating the entire drainage basin as if it were a lake. The response coefficient k_L will then reflect the response character of the basin. Song et al. (1973) suggested that this coefficient decreases as the basin drainage area increases.

Equations 7 and 9 describe variations of water temperature when the air temperature is expressed as a simple harmonic function T_N in the form of eq 6. To incorporate variations of air temperature with a period less than 1 year, estimated from the weather forecast, the air temperature should be approximated by a combination of T_N and a series of short-term deviations as shown in Figure 3.

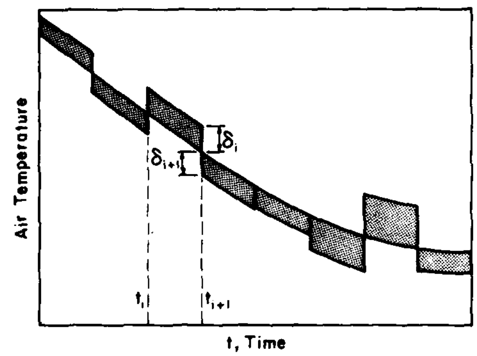


Figure 3. Analytical representation of a series of short-term forecasts for air temperature.

The short-term deviation from T_N can be written as

$$\delta T_a^i = \begin{cases} \delta_i \text{ ; when } t_i \leq t \leq t_{i+1} \\ 0 \text{ ; otherwise .} \end{cases} \tag{11}$$

For a well-mixed lake the effect of δT_a^i on water temperature is

$$\delta T_L = \begin{cases} 0 & \text{; when } t_L < t_i \\ \delta_i[1-e^{-k_L(t_L-t_i)}] & \text{; when } t_i \leq t_L \leq t_{i+1} \\ \delta_i[e^{-k_L(t_L-t_{i+1})}-e^{-k_L(t_L-t_i)}] & \text{; when } t_L > t_{i+1}. \end{cases} \tag{12}$$

For a river reach as defined in Figure 2, the effect of δT_a^i is

a) when $t - t_{T_j} < t_i$:

$$\delta T_{j+1} = \begin{cases} 0 & ; t < t_i \\ \delta_i [1 - e^{-k_j(t-t_i)}] & ; t_i \leq t \leq t_{i+1} \\ \delta_i [e^{-k_j(t-t_{i+1})} - e^{-k_j(t-t_i)}] & ; t > t_{i+1} \end{cases} \tag{13}$$

b) when $t_i \leq t - t_{T_j} \leq t_{i+1}$:

$$\delta T_{j+1} = \begin{cases} 0 & ; t < t - t_{T_j} \\ \delta_i [1 - e^{-k_j t_{T_j}}] & ; t - t_{T_j} \leq t \leq t_{i+1} \\ \delta_i [e^{-k_j(t-t_{i+1})} - e^{-k_j t_{T_j}}] & ; t > t_{i+1} \end{cases} \tag{14}$$

c) when $t - t_{T_j} > t_{i+1}$:

$$\delta T_{j+1} = 0 \,. \tag{15}$$

A complete solution for river water temperature including short-term variations can be obtained by linear superpositions of δT_{j+1} to T_{j+1} and δT_L to T_L.

APPLICATION TO THE UPPER ST. LAWRENCE RIVER

The upper St. Lawrence River, which is the outlet from Lake Ontario, extends approximately 160 km from Kingston, Ontario, to the Moses-Saunders Power Dam near Massena, New York (Fig. 4). The river is utilized for navigation and hydropower production. When the river freezes up, navigation must cease and head losses increase. The formation of the ice cover also reduces the conveyance capacity of the river and affects the Lake Ontario water level. The ability to predict the freeze-up date is therefore important in managing various activities on the river.

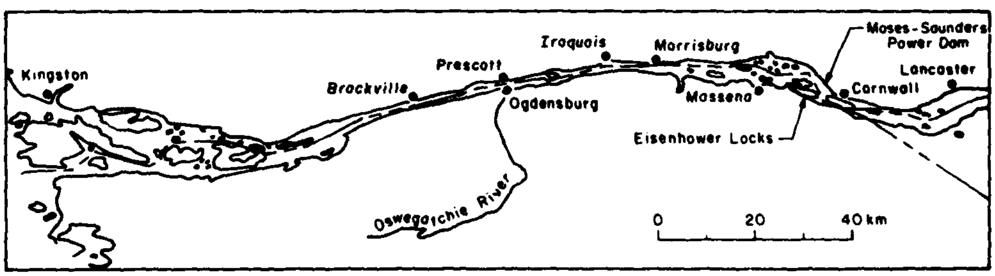


Figure 4. Plan of St. Lawrence River, Lake Ontario to Moses-Saunders Power Dam (after Witherspoon and Poulin 1970).

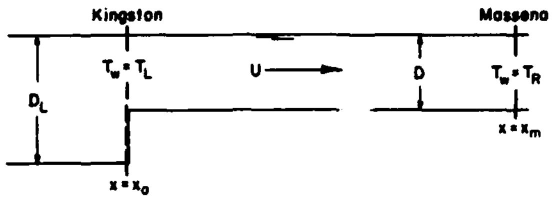


Figure 5. Schematic representation of the upper St. Lawrence River.

If we simplify the river as shown in Figure 5 and assume that the air temperature over the entire river length is the same, then the normal water temperature at Massena can be obtained from eq 7:

$$T_{R,N} = \overline{T} + a \cos\alpha_R \sin\left(\frac{2\pi t}{T} + \theta - \alpha_R\right)$$

$$+ \exp(-k_R t_T)\left[T_{L,N} - \overline{T} - a \cos\alpha_R \sin\left(\frac{2\pi t}{T} + \theta - \alpha_R\right)\right] \tag{16}$$

where $T_{R,N}$ = normal water temperature at time t
t_T = travel time between Kingston and Massena, $(x_m - x_o)/U$
U = mean flow velocity
$k_R = h_{wa}/(\rho C_p D)$
D = average depth of flow between Kingston and Massena
$\alpha_R = \tan^{-1}(2\pi/k_R T)$

and where

$$T_{L,N} = \overline{T} + a \cos\alpha_L \sin\left(\frac{2\pi t}{T} + \theta - \alpha_L\right)$$

$$+ \exp[-k_L(t_L - t_o)]\left[T_o - \overline{T} - a \cos\alpha_L \sin\left(\frac{2\pi t_o}{T} + \theta - \alpha_L\right)\right] \tag{17}$$

where $T_{L,N}$ = Kingston normal water temperature at time t_L
$t_L = t - t_T$
t_o = initial time
$k_L = h_{wa}/(\rho C_p D_L)$
$\alpha_L = \tan^{-1}(2\pi/k_L T)$
D_L = effective depth of water at Kingston.

Equations 16 and 17 are analytical expressions for water temperature at Kingston and Massena when the air temperature is approximated by T_N. To include the effect of forecasted deviations of air temperature from T_N, the Kingston water temperature during each time interval can be computed by

$$e^{-k_L(t_L - t_i)} = \frac{T_L - (\overline{T} + \delta_i) - a \cos\alpha_L \sin\left(\frac{2\pi t_L}{T} + \theta - \alpha_L\right)}{T_L^{(i)} - (\overline{T} + \delta_i) - a \cos\alpha_L \sin\left(\frac{2\pi t_i}{T} + \theta - \alpha_L\right)};$$

when $t_i \leq t_L \leq t_{i+1}$ (18)

where T_L = Kingston water temperature at time t_L

$T_L^{(i)}$ = Kingston water temperature at time t_i

δ_i = air temperature deviation for the ith time period.

The water temperature at Massena can be approximated by

$$e^{-k_R t_T} = \frac{T_R - (\overline{T} + \delta_i) - a \cos\alpha_R \sin\left(\frac{2\pi t}{T} + \theta - \alpha_R\right)}{T_L - (\overline{T} + \delta_i) - a \cos\alpha_R \sin\left(\frac{2\pi t_L}{T} + \theta - \alpha_R\right)} \tag{19}$$

when $t_i \leq t \leq t_{i+1}$

where T_R is the Massena water temperature at time t. When t_L is in the (i-1)th time interval and t is in the ith time interval, eq 19 is not strictly valid, since it does not account for the change in air temperature deviation from one time interval to another. However, eq 19 is used, since it is easier to apply and the accuracy of air temperature forecast does not warrant the effort of calculating the exact solution from eq 13-15.

Parameters k_L and k_R can either be estimated from the average depth of the flow in the river and the surface heat exchange coefficient or be determined from recorded air and water temperature data by nonlinear regression analyses. The latter approach is more accurate and is used in this study. Since the flow depth in the St. Lawrence River remains relatively constant over time, k_L and k_R values are considered to be constants. For rivers with large variations of flow depth, these coefficients should be treated as functions of D. Based on data for the period between 1965 and 1981, k_L and k_R are determined by the NLIN procedure of SAS Institute Inc. (1982) using half-month intervals. Table 3 summarizes the model parameters for the upper St. Lawrence River.

Table 3. Model parameters for the upper St. Lawrence River.

Model parameter	*Estimated value*	*Standard error*
Mean air temperature T	6.639°C	0.042°C
Fourier coefficient C_1	5.869°C	0.059°C
Fourier coefficient S_1	-13.093°C	0.059°C
Response parameter k_L	0.0191 day^{-1}	0.00105 day^{-1}
Response parameter k_R	0.0345 day^{-1}	0.00182 day^{-1}

Previous studies (Joint Board of Engineers 1926, Witherspoon and Poulin 1970, Adams 1976) have shown that the heat exchange coefficient h_{wa} for the study reach is about 21.7 W/m^2°C. Values of k_L and k_R given in Table 3 correspond to an effective water depth of 23.56 m at Kingston and an average depth of 13.04 m for the river flow between Kingston and Massena.

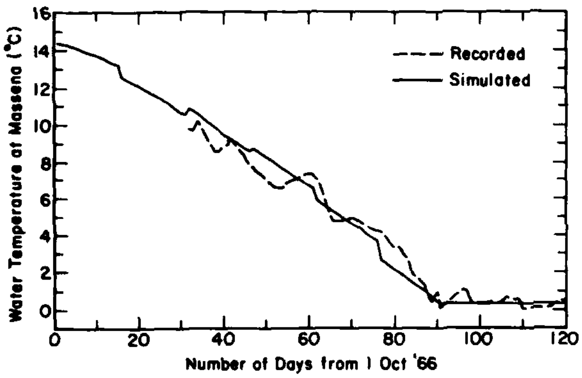
A computer program for forecasting freeze-up at Massena was developed and is presented in Appendix A. The freeze-up at Massena is defined as the date on which the water temperature at the Moses-Saunders Dam declined to 0.3°C (Assel 1976, 1977). At that time it is probable that an ice cover has formed from shore to shore in the Eisenhower Lock area. The input data required for the freeze-up forecast include the initial water temperature at Kingston, the long-range forecast for air temperature deviation from the normal air temperature at Massena, and the predicted discharge at Moses-Saunders Power Dam. The air temperature deviation can be estimated from the weather outlook provided by the National Weather Service along with the standard deviation of air temperature given in Table 4. Table 4 shows large fluctuations in T_a during December and January.

A sample freeze-up forecast beginning on 1 December 1983 is included in Appendix A. The measured water temperature at Kingston on 30 November 1983 was 7°C, the air temperature forecast was 1.5°C below normal for 1 December to 15 December 1983 and 5°C below normal for 16 December to 31 December, and the forecasted travel time was 9 days. The model forecasted a freeze-up date of 24 December 1983, which turned out to be the day of the actual freeze-up.

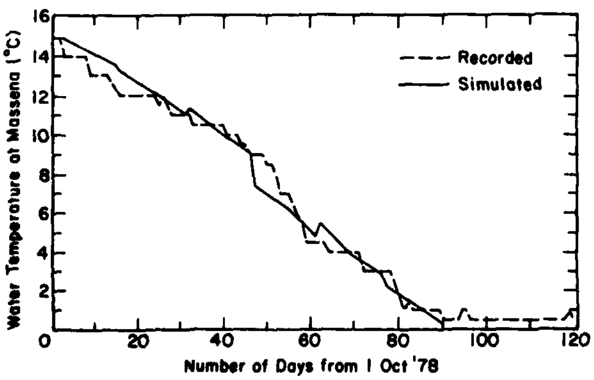
To test the accuracy of the forecast model, freeze-up dates were calculated for the 16 years between 1965 and 1981 using recorded air and water temperature data. Simulated and recorded water temperature declines for two seasons are presented in Figure 6. The observed and simulated freeze-up dates for all 16 years are summarized in Table 5. Confidence limits for forecasts with different beginning dates of simulation are presented in Table 6 and Figure 7. Large discrepancies between the simulated and recorded freeze-up dates during a

Table 4. Semi-monthly standard deviations of Massena air temperature from first harmonic.

Time period		*Standard Deviation (°C)*
Oct.	1-15	4.500
	16-31	4.496
Nov.	1-15	4.527
	16-30	5.108
Dec.	1-15	5.718
	16-31	5.694
Jan.	1-15	5.416
	16-31	5.159
Feb.	1-15	5.087
	16-29	5.398
Mar.	1-15	4.973
	16-31	4.854
Apr.	1-15	4.097
	16-30	4.121
May	1-15	4.471
	16-31	4.361
Jun.	1-15	3.900
	16-30	3.440
Jul.	1-15	3.195
	16-31	3.085
Aug.	1-15	3.307
	16-31	3.691
Sep.	1-15	4.021
	16-30	4.246



a. 1966–67.



b. 1978–79.

Figure 6. Recorded and simulated water temperature, Massena, New York.

Table 5. Observed and simulated freeze-up dates, St. Lawrence River at Massena, 1965-1980.

Year	Observed freeze-up	Forecasted freeze-up					
		1 Oct	16 Oct	1 Nov	16 Nov	1 Dec	16 Dec
1965-66	8 Jan	1 Jan -7	1 Jan -7	1 Jan -7	1 Jan -7	1 Jan -7	3 Jan -5
1966-67	30 Dec	29 Dec -1	29 Dec -1	30 Dec 0	29 Dec -1	30 Jan 0	11 Jan +12
1967-68	3 Jan	29 Dec -5	28 Dec -6	28 Dec -6	27 Dec -7	29 Jan -5	1 Jan -2
1968-69	25 Dec	28 Dec +3	26 Dec +1	26 Dec +1	25 Dec 0	26 Dec +1	26 Dec +1
1969-70	28 Dec	25 Dec -3	24 Dec -4	23 Dec -5	23 Dec -5	23 Dec -5	27 Dec -5
1970-71	23 Dec	30 Dec +7	30 Dec +7	29 Dec +6	29 Dec +6	25 Dec +2	27 Dec +4
1971-72	8 Jan	31 Jan -8	30 Dec -9	31 Jan -8	30 Dec -9	31 Jan -8	8 Jan 0
1972-73	21 Dec	24 Dec +3	23 Dec +2	23 Dec +2	22 Dec +1	24 Dec +3	25 Dec +4
1973-74	30 Dec	1 Jan +2	1 Jan +2	1 Jan +2	30 Dec 0	1 Jan +2	1 Jan +2
1974-75	22 Jan	18 Jan -4	14 Jan -8	14 Jan -8	10 Jan -12	21 Jan -1	23 Jan +1
1975-76	27 Dec	27 Dec 0	27 Dec 0	27 Dec 0	28 Dec +1	27 Dec 0	28 Dec +1
1976-77	14 Dec	22 Dec +8	21 Dec +7	17 Dec +3	18 Dec +4	15 Dec +1	15 Dec +1
1977-78	30 Dec	1 Jan +2	29 Dec +1	30 Dec 0	28 Dec -2	No Kingston Data 11/23-12/31	
1978-79	28 Dec	28 Dec -2	27 Dec -3	27 Dec -3	27 Dec -3	26 Dec -4	10 Jan +1
1979-80	12 Jan	12 Jan 0	11 Jan -1	11 Jan -1	12 Jan 0	13 Jan +1	10 Jan -2
1980-81	21 Dec	16 Dec -5	16 Dec -5	16 Dec -5	16 Dec -5	16 Dec -5	16 Dec -5
Mean		-0.625	-0.625	-1.813	-2.438	-1.667	+0.800

Table 6. Confidence limits of the freeze-up forecast.

	Oct. 1	*Oct. 16*	*Nov. 1*	*Nov. 16*	*Dec. 1*	*Dec. 16*
95% upper limit	1.86	0.94	0.47	0.12	0.34	3.07
80% upper limit	0.94	-0.01	-0.38	-0.83	-0.41	2.22
50% upper limit	0.18	-0.79	-1.07	-1.61	-1.02	1.53
Mean error	-0.63	-1.63	-1.81	-2.44	-1.67	0.80
50% lower limit	-1.43	-2.46	-2.55	-3.27	-2.31	0.07
80% lower limit	-2.19	-3.24	-3.25	-4.05	-2.92	-0.62
95% lower limit	-3.11	-4.19	-4.09	-5.00	-3.67	-1.47

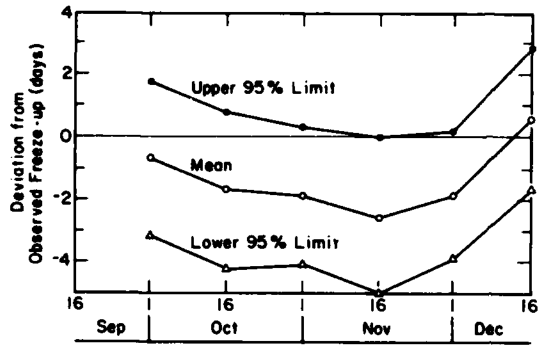


Figure 7. Confidence limits for the deviation of forecasted freeze-up date from the observed date.

few winters may be attributed to the simplicity of the freeze-up criteria used. The water temperature at Massena may fluctuate around 0.3°C over a period of several weeks. During this period the forecast area may alternately freeze and thaw. The use of a single date for the freeze-up is inadequate in describing this phenomenon. The inability of a constant surface heat exchange coefficient to account for some of the meteorological phenomena, such as snowfalls and extreme wind conditions, may also contribute to the discrepancies in the freeze-up forecast.

SUMMARY

In this report a method for making long-range forecasts of river freeze-up is developed. It is shown that the water temperature decline in a river is governed by the convection of the water mass in the river and the heat exchange at the free surface. The surface heat exchange can be expressed in terms of the difference between the water temperature and the ambient air temperature. The air temperature can be effectively represented by a linear combination of the normal air temperature described by a harmonic function with a period of one year and short-term variations obtained from the National Weather Service. The application of this mehtod to the St. Lawrence River between Kingston and Massena shows that it is capable of providing accurate freeze-up forecasts.

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APPENDIX A. BASIC PROGRAM FOR ST. LAWRENCE RIVER FREEZE-UP FORECAST

```
LIST

1   REM ****************************************************************
2   REM
3   REM  INPUT TO ST LAWRENCE RIVER FREEZE-UP MODEL
4   REM  TO = INITIAL DATE OF FORECAST IN DAYS FROM OCTOBER 1
5   REM  D1-D8 = FORECASTED AIR TEMP DEVIATION FROM NORMAL IN DEG C
6   REM  TWO = KINGSTON WATER TEMP IN DEG C ON FIRST DAY OF FORECAST
7   REM  TT = TRAVEL TIME IN DAYS FROM KINGSTON TO MASSENA (2.1303E6/Q)
8   REM  IYEAR% = YEAR OF FORECAST
9   REM ****************************************************************
10 KL = 0.01910924
15 T1L = 2.72018 -  ATN (0.01721 / KL)
20 KR = 0.03452020
25 T2R = 2.72018 -  ATN (0.01721 / KR)
30 CL = 1 /  SQR (1 + (0.01721 / KL) ^ 2)
40 CR = 1 /  SQR (1 + (0.01721 / KR) ^ 2)
44  REM
45  REM   INPUT TEMP DEVIATIONS AND INITIAL CONDITIONS
46  REM
50  READ TO,D1,D2,D3,D4,D5,D6,D7,D8,TWO,TT,IYEAR%
60  IF TO >  = 1 AND TO <  = 31 THEN ID% = TO
70  IF TO >  = 32 AND TO <  = 61 THEN ID% = TO - 31
80  IF TO >  = 62 AND TO <  = 92 THEN ID% = TO - 61
90  IF TO >  = 93 THEN ID% = TO - 92
94  PRINT
95  PRINT
96  PRINT
100  IF TO >  = 1 AND TO <  = 31 THEN  PRINT "THE OCTOBER ";ID%;
110  IF TO >  = 32 AND TO <  = 61 THEN  PRINT "THE NOVEMBER ";ID%;
120  IF TO >  = 62 AND TO <  = 92 THEN  PRINT "THE DECEMBER ";ID%;
130  IF TO >  = 93 THEN  PRINT "THE JANUARY ";ID%;
140  PRINT " FORECAST AT MASSENA, N.Y. FOR ";IYEAR%
150 IB =  INT (TO)
154  REM
155  REM  START LOOP TO COMPUTE MASSENA WATER TEMPERATURE
156  REM
160  FOR IT = IB TO 123
170 TIME = IT
180 TMTT = TIME - TT
184  REM
185  REM  UPDATE LAKE TEMP, AIR TEMP DEVIATIONS, AND CHECK FOR NEW TO
186  REM
190  IF TIME = 16 OR TIME = 32 OR TIME = 47 THEN  GOSUB 660
200  IF TIME = 62 OR TIME = 77 OR TIME = 93 THEN  GOSUB 660
210  IF TIME >  = 1 AND TIME <  = 15 THEN DR = D1
220  IF TIME >  = 16 AND TIME <  = 31 THEN DR = D2
230  IF TIME >  = 32 AND TIME <  = 46 THEN DR = D3
240  IF TIME >  = 47 AND TIME <  = 61 THEN DR = D4
250  IF TIME >  = 62 AND TIME <  = 76 THEN DR = D5
260  IF TIME >  = 77 AND TIME <  = 92 THEN DR = D6
270  IF TIME >  = 93 AND TIME <  = 107 THEN DR = D7
280  IF TIME > 107 THEN DR = D8
290  IF TMTT <  = 15 THEN DL = D1
300  IF TMTT >  = 16 AND TMTT <  = 31 THEN DL = D2
310  IF TMTT >  = 32 AND TMTT <  = 46 THEN DL = D3
320  IF TMTT >  = 47 AND TMTT <  = 61 THEN DL = D4
330  IF TMTT >  = 62 AND TMTT <  = 76 THEN DL = D5
```

```
340  IF TMTT >  = 77 AND TMTT <  = 92 THEN DL = D6
350  IF TMTT >  = 93 AND TMTT <  = 107 THEN DL = D7
360  IF TMTT > 107 THEN DL = D8
370  IF TIME = 16 THEN TO = 15
380  IF TIME = 32 THEN TO = 31
390  IF TIME = 47 THEN TO = 46
400  IF TIME = 62 THEN TO = 61
410  IF TIME = 77 THEN TO = 76
420  IF TIME = 93 THEN TO = 92
430  IF TIME = 107 THEN TO = 106
434  REM
435  REM  COMPUTE MASSENA RIVER TEMP
436  REM
440 A1 = 0.01721 * TIME + T2R
450 A3 = 0.01721 * TMTT + T2R
460 ER =  EXP ( - KR * TT)
470 XD = TIME
480  GOSUB 700
490 A = 6.639 + DR
500 B = (TL - 6.639 - DR) * ER
510 C = 14.348 * CR *  SIN (A1)
520 D = 14.348 * ER * CR *  SIN (A3)
530 TR = A + B + C - D
535  PRINT " TIME= ";TIME;" DAYS,RIVER TEMP= ";TR;" DEG C"
540  IF TR <  = 0.3 THEN  GOTO 570
550  NEXT IT
560  PRINT "THE DATE OF FREEZE-UP WAS NOT REACHED BY JANUARY 31"
564  REM
565  REM  DETERMINE CALENDAR DATE OF FREEZE-UP
566  REM
570  IF TIME <  = 92 GOTO 610
580 ID% = TIME - 92
590  PRINT "THE DATE OF FREEZE-UP IS JANUARY ";ID%
600  GOTO 630
610 ID% = TIME - 61
620  PRINT "THE DATE OF FREEZE-UP IS DECEMBER ";ID%
630  REM
640  GOTO 50
650  END
654  REM
655  REM  SUBROUTINE TO UPDATE LAKE TEMP AT EACH
656  REM       CHANGE OF AIR TEMP DEVIATION
657  REM
660 XD = TIME + TT
670  GOSUB 700
680 TWO = TL
690  RETURN
694  REM
695  REM  SUBROUTINE TO COMPUTE LAKE TEMP
696  REM
700 A2 = 0.01721 * (XD - TT) + T1L
710 A4 = 0.01721 * (TO) + T1L
720 EL =  EXP ( - KL * (XD - TT - TO))
730 A = 6.639 + DL
740 B = (TWO - 6.639 - DL) * EL
750 C = 14.348 * CL *  SIN (A2)
760 D = 14.348 * EL * CL *  SIN (A4)
770 TL = A + B + C - D
780  RETURN
790  DATA  62,0,0,0,0,-1.5,-5,0,0,7,9.8384
```

```
RUN

THE DECEMBER 1 FORECAST AT MASSENA, N.Y. FOR 8384
 TIME= 62 DAYS,RIVER TEMP= 5.3980055 DEG C
 TIME= 63 DAYS,RIVER TEMP= 5.22429169 DEG C
 TIME= 64 DAYS,RIVER TEMP= 5.0504605 DEG C
 TIME= 65 DAYS,RIVER TEMP= 4.8765714 DEG C
 TIME= 66 DAYS,RIVER TEMP= 4.70268361 DEG C
 TIME= 67 DAYS,RIVER TEMP= 4.52885622 DEG C
 TIME= 68 DAYS,RIVER TEMP= 4.35514823 DEG C
 TIME= 69 DAYS,RIVER TEMP= 4.18161835 DEG C
 TIME= 70 DAYS,RIVER TEMP= 4.00832524 DEG C
 TIME= 71 DAYS,RIVER TEMP= 3.81451759 DEG C
 TIME= 72 DAYS,RIVER TEMP= 3.62145706 DEG C
 TIME= 73 DAYS,RIVER TEMP= 3.42919415 DEG C
 TIME= 74 DAYS,RIVER TEMP= 3.23777917 DEG C
 TIME= 75 DAYS,RIVER TEMP= 3.0472624 DEG C
 TIME= 76 DAYS,RIVER TEMP= 2.8576939 DEG C
 TIME= 77 DAYS,RIVER TEMP= 1.57073723 DEG C
 TIME= 78 DAYS,RIVER TEMP= 1.38631337 DEG C
 TIME= 79 DAYS,RIVER TEMP= 1.20292832 DEG C
 TIME= 80 DAYS,RIVER TEMP= 1.02063256 DEG C
 TIME= 81 DAYS,RIVER TEMP= .839476316 DEG C
 TIME= 82 DAYS,RIVER TEMP= .659509452 DEG C
 TIME= 83 DAYS,RIVER TEMP= .480781701 DEG C
 TIME= 84 DAYS,RIVER TEMP= .303342351 DEG C
 TIME= 85 DAYS,RIVER TEMP= .127240472 DEG C
THE DATE OF FREEZE-UP IS DECEMBER 24

?OUT OF DATA ERROR IN 50
```

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